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Bellcomm

955 L'Enfant Plaza North, S.W.
Washington, D. C. 20024

date: March 31, 1972

to: Distribution

from: W. Levidow

B72 03015

subject: Skylab CMG Gimbal Angle Behavior and Attitude Control Performance
Case 620

ABSTRACT

Attitude control torque for the Skylab is provided by three gimbaled Control Moment Gyros (CMGs). By driving the gimbal angles, sufficient torque should normally be developed to counteract disturbance torques and also execute spacecraft maneuvers.

At times, the developed torque may not equal the required torque because:

1. mechanical and electrical stops limit gimbal angle rotation,

2. gimbal rates are limited,

3. the steering law commands inadequate torque at low values of CMG momentum magnitude.

A simulation of 3 CMG control for solar inertial orbits, dump maneuvers, and Z-local vertical passes did not disclose control problems.

However, with 2 CMG control, up to 20 lb-sec of TACS propellant assistance was required for some solar inertial orbits and up to 791 lb-sec was required for some 60° Z-local vertical passes. On some dump maneuvers, attitude control was ineffective, resulting in attitude errors up to 48°. These problems require attention.

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MEMORANDUM FOR FILE

Introduction

Three double gimbaled control moment gyros (CMGs) are used to develop torque for attitude control of the Skylab. The gimbal rate commands are a function of the vehicle attitude and rotational rate errors.

Several limitations[1] are imposed on the movement of the gimbals and hence on the developed torque:

1. Mechanical and electrical stops limit gimbal angle rotations, from nominal, to approximately ±175° for the outer gimbals and ±80° for the inner gimbals. The gimbal rate commands are reduced as the gimbal stops are approached.

2. At other times the gimbal rates are limited to values within the capacity of the gimbal torque motors.

3. The steering law has been modified at low values of CMG momentum magnitude in order to overcome its inability to command torque for the 2 CMG, zero momentum magnitude case. However, even with this modification, at low momentum magnitude the commanded torque does not necessarily equal, in magnitude or direction, that required by the control law.

These restraints may act to limit the developed torque below that required for satisfactory attitude control. This danger is particularly present during 2 CMG operation, when each gyro movement must be faster to compensate for the loss of the third gyro. Also, a gimbal stop encounter during 2 CMG operation results in loss of three axis attitude control.

This memorandum reports the investigation, by means of a computer simulation, of the adequacy of CMG attitude control of typical solar inertial (including momentum dump maneuvers) and z-local vertical (ZLV) pass orbits.

Solar Inertial (including momentum dump) Orbits

Solar inertial orbits for η_x^* = 0, ± 30°, and ± 70° were initiated at 90° after dump midnight. The gimbal angles were initialized by a caging command, driving them from their nominal values (outer = 45°, inner = 0°) to those corresponding to the momentum state approximately optimal for that orbital position.†

The assumed[2] venting, leakage, aerodynamic drag, and gravity gradient torques produced bias momentum requiring the following momentum dump commands:

η_x	Momentum Dump Command, ft-lb-sec		
	X	Y	Z
0°	80	-1615	6
+30°	315	-1550	900
-30°	65	-1035	-600
+70°	500	- 450	1600
-70°	400	270	1000

No difficulty was experienced in maintaining 3 CMG attitude control. The maximum gimbal angles from nominal were 80° for the outer gimbals and 45° for the inner gimbals.

However, as shown in Table 1, 2 CMG control did present some problems. For reporting purposes, each orbit is separated into a solar inertial (SI) phase and a dump phase. The SI phase

*Angle of the vehicle z body axis below the orbital plane.

†Defined by Ref. 1, Eq. 12.7.3. Assuming no momentum biasing, this equation yields a momentum of 3200 ft-lb-sec directed above and normal to the orbital plane.

is the half orbit from 6 A.M. to 6 P.M., with respect to dump midnight, and the dump phase is the half orbit from 6 P.M. to 6 A.M.

A dash "-" entry indicates satisfactory performance whereas an "x" indicates unsatisfactory or at least questionable performance. An "x" in the "Hit stop" column indicates that a gimbal rate has been limited during the phase because of a gimbal stop encounter.

The maximum attitude error on any axis during a phase is indicated by "ϕ_e". If the major cause of the error is from encountering the gimbal stop it is so indicated by "GS" after the error, if from gimbal rate limiting it is indicated by "RL", and if from low magnitude of momentum it is indicated by "$\underline{H}$".

Excessive attitude error requires TACS propellant usage for attitude control. The TACS propellant required from the simulation is indicated for the SI phase. TACS is inhibited during dumping because moderate attitude errors can be tolerated during dumping without critically affecting performance.

During the Skylab mission, caging of the gimbal angles to the momentum corresponding to the orbital position may be requested whenever the actual CMG momentum or gimbal angles appear to be abnormal. This implies that satisfactory gimbal action should be expected following caging. Because the momentum excursions for the above phases are nearly symmetrical about noon and midnight, it is expected that the gimbal angle excursions for each phase also exhibit a symmetrical pattern, tracking their caged values. The angles at the end of the phase should nearly equal those at the start. However, on several of the orbits studied, the gimbal angles at the end of the phase did not correspond to their caged values, and the gimbal angle patterns were quite asymmetrical.† These cases are marked by an "x" under the "Digress" column. When this occurred during the SI phase, the dump phase was rerun (indicated by "Dump (c)") after first caging to the momentum state optimal for the 6 P.M. orbital position. This procedure evauated the dump phase for both the caged and non-caged initial gimbal angles.

The rotation law which influences the gimbal angles in order to minimize the probability of a gimbal stop encounter, is often inhibited by limitations placed on the magnitude of the "S"*

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*Ref. 1, Eq. 12.5.28 - 39.

†The occurrence of markedly different gimbal angles upon return to the same momentum conditions is a consequence of the multiple equilibrium phenomena associated with the CMG rotation law (See Ref. 3).

functions. In cases where the gimbal angles digressed from the caged values, the simulation was rerun with the limitation removed in order to determine if the limitation allowed the digression. An "s" in the table indicates that removing the limitation prevented the gimbal stop encounter or prevented digression from the caged values. An "$\not{s}$" indicates that removing the limitation did not improve the performance.

The outcome of the simulations will be discussed case by case, adding tests and results not included in the table.

$\underline{n}_x$ = 0, #1 CMG out

The performance was satisfactory. The gimbal angles exhibited symmetrical patterns over each phase with maximum angles from nominal of 96° for the outer gimbal and 56° for the inner.

$\underline{n}_x$ = 0, #2 CMG out

As indicated by the $\underline{H}$, the 0.4° attitude error was the result mainly of inadequate commanded torque as the CMG momentum state passed briefly through a period of low magnitude.

Gimbal rate limitation was a minor factor since reruning the SI phase with the rate limitation removed decreased the attitude error to 0.3°.

$\underline{n}_x$ = 0°, #3 CMG out

During the SI phase #1 CMG inner gimbal encountered its stop at noon, requiring 20 lb-sec of TACS propellant for attitude control. (A rerun without the "S" function limitation eliminated both the gimbal stop encounter and the need for TACS propellant.)

During the dump phase #1 CMG encountered its stop at the transition from the first to the second dump velocity, but quickly recovered. The brief 9° attitude error during dumping resulted in only a 2% change in the momentum dumped from that if there were no attitude error. (A rerun without the "S" function limitation eliminated the gimbal stop encounter and resulted in only a 0.2° attitude error.)

$\underline{n}_x$ = 30°, #1 CMG out

During the SI phase #3 CMG outer gimbal briefly encountered its stop before noon and required 20 lb-sec of TACS propellant. (A rerun without the "S" function limitation eliminated the gimbal stop encounter but still required 16 lb-sec of TACS propellant for attitude control during a period of small momentum magnitude.)

During the dump phase a 0.4° attitude error developed and the gimbal angles digressed from caged values. Starting the dump phase from caged values did not improve performance.

$\underline{n}_x$ = 30° #2 CMG out

During the dump phase the #1 CMG outer gimbal briefly encountered its stop causing a 2° attitude error. (A rerun without the "s" function limitation eliminated the gimbal stop encounter.)

$\underline{n}_x$ = 30°, #3 CMG out

During the SI phase the #2 CMG inner gimbal briefly encountered its stop. However, the 16 lb-sec of TACS propellant resulted from insufficient CMG torque at low momentum magnitude. (A rerun without the "S" function limitation eliminated the gimbal stop encounter and the digression, but the 16 lb-sec of propellant was still required.)

Starting the dump phase with caged gimbal angles resulted in a brief gimbal stop encounters of #1 and #2 CMG outer gimbals.

$\underline{n}_x$ = -30°, #1 CMG out

The SI phase ended with non caged values of gimbal angles. A subsequent dump and SI phase exhibited symmetrical gimbal angle excursions but their initial and final values were radically different from their corresponding caged values. However, if the dump phase started with caged values, then it ended with caged values. (Removing the "S" function limitation resulted in caged values of gimbal angles for both the SI and dump phases. Also, the gimbals did not approach as close to their stops.)

$\underline{n_x = -30°\text{, \#2 CMG out}}$

A 0.6° attitude error developed during SI due to low momentum magnitude.

$\underline{n_x = -30°\text{, \#3 CMG out}}$

A 0.4° attitude error developed during SI due to low momentum magnitude.

$\underline{n_x = +70°\text{, \#1 CMG out}}$

During the SI phase #2 CMG outer gimbal encountered its stop briefly at noon, not long enough to cause a significant attitude error. Gimbal rate limiting caused attitude errors of 0.2° at two brief intervals. (A rerun with the "S" function limitation removed eliminated the gimbal stop encounter but did not prevent the gimbal angle digression from caged values.)

#2 CMG outer gimbal encountered its stop during the first dump velocity and #3 CMG outer gimbal encountered its stop during the transition from the first to the second dump velocity. The encounters were brief, resulting in 2.5° maximum attitude error. Although the gimbal angles at 6 P.M. were non-caged values, they reverted to caged values by the end of the dump maneuvers. (Removing the "S" function limitation eliminated the gimbal stop encounter.)

Starting the dump phase with caged gimbal angles resulted in digression and in a #2 CMG outer gimbal stop encounter during the entire third dump velocity maneuver. (A rerun without the "S" function limitation eliminated both the gimbal stop digression and the encounter.)

$\underline{n_x = +70°\text{, \#2 CMG out}}$

A 0.5° attitude error developed during SI due to low momentum magnitude.

$\eta_x = +70°$, #3 CMG out

The performance was satisfactory.

$\eta_x = -70°$, #1 CMG out

The #2 CMG outer gimbal encountered its stop during the transition from the first to the second dump velocity and hung there until 6 A.M. At that point the attitude error exceeded 48° about the Z axis and 19° about the Y axis. (Removing the "S" function limitation resulted in almost identical performance.)

$\eta_x = -70°$ #2 CMG out

The performance was satisfactory.

$\eta_x = -70°$, #3 CMG out

Both #1 and #2 CMG outer gimbals encountered their stops during the transition from the first to the second dump velocity and hung there until 6 A.M. At that point the attitude error exceeded 40° about the z axis and 11° about the Y axis. (Removing the "S" function limitation resulted in almost identical performance until the transition from the second to the third dump velocity. At that point both outer gimbals broke away from their stops.)

As a further test of performance, the dump phases at $\eta_x = \pm 70°$ and #2 CMG out were rerun, caging the gimbal angles at 6 P.M. to 2800 ft-lb-sec instead of 3200. The difference is within the range of momentum biasing that may be required to center the momentum variation within the saturation limits. At $\eta_x = -70°$, the performance was satisfactory. At $\eta_x = +70°$, both the #1 and #3 CMG outer gimbals encountered their stops during the transition from the second to the third dump velocity and hung there until 6 A.M. Attitude error exceeded 20° on the Y axis. (Removing the "S" function limitation eliminated the gimbal stop encounter and resulted in satisfactory performance.) The outcome of this test indicates that Table 1 might appear quite different for other assumed initial momentum states.

Z - Local Vertical Passes

Z-local vertical passes centered at noon were simulated for $\eta_x = 0°$ and $\eta_x = \pm 50°$. The vehicle maneuver to the Z-LV attitude was initiated 110° before noon and the maneuver from the Z-LV attitude terminated 110° after noon. Just prior to the initiation of the first maneuver the gimbal angles were caged to the gimbal angles corresponding to the momentum state expected for that orbital position.

There were no gimbal angle problems with 3 CMG control on either 60° or 120° passes. The 120° pass caused CMG momentum saturation and required 24 lb-sec of TACS propellant. The maximum gimbal angles from center were:

Z-LV Pass	Outer	Inner
60°	60°	50°
120°	125°	75°

Table 2 shows the results for 2 CMG control of 60° passes. The symbols are the same as for Table 1.

$\underline{n}_x$ = 0°, #1 CMG out

The performance was satisfactory. The gimbal angles exhibited a symmetrical pattern and the maximum angles from center were 116° on an outer gimbal and 65° on an inner.

$\underline{n}_x$ = 0°, #2 CMG out

The performance was satisfactory.

$\underline{n}_x$ = 0°, #3 CMG out

The #1 CMG outer gimbal encountered its stop briefly during the first maneuver and the #2 CMG outer gimbal encountered its stop during most of the Z-LV pass and again during the second maneuver. Attitude control required 583 lb-sec of TACS propellant. (Reruning without the "S" function limitation eliminated the gimbal stop encounter and the digression.)

$\underline{n}_x$ = 50°, #1 CMG out

The #3 CMG inner gimbal encountered its stop briefly during the first vehicle maneuver and again during most of the Z-LV pass. (Rerunning without the "S" function limitation caused both the #2 CMG outer and the #3 CMG inner gimbals to encounter their stops.)

$\underline{n_x = 50°, \#2\ \text{CMG out}}$

Performance was satisfactory until initiation of the second maneuver. At that time 76 lb-sec of TACS was required for attitude control caused be inadequate CMG torque due to small momentum magnitude. This TACS firing altered the CMG momentum thereafter such that CMG momentum saturation was reached during the velocity change from the second maneuver to the SI attitude. An additional 61 lb-sec of TACS was then required for momentum management. (Removing the "S" function limitation does not improve the performance.)

$\underline{n_x = 50°, \#3\ \text{CMG out}}$

The #2 CMG outer gimbal encountered its stop during the Z-LV pass and the #1 CMG outer gimbal encountered its stop during the maneuver back to SI.

$\underline{n_x = -50°, \#1\ \text{CMG out}}$

A total of 199 lb-sec of TACS was required for attitude control at the transitions between the first maneuver and the Z-LV pass, between the pass and the second maneuver, and at the termination of the second maneuver.

$\underline{n_x = -50°, \#2\ \text{CMG out}}$

The performance was satisfactory.

$\underline{n_x = -50°, \#3\ \text{CMG out}}$

The #1 CMG outer gimbal briefly encountered its stop during the second maneuver. A total of 791 lb-sec of TACS was required mostly for attitude error control during the angular velocity changes at the start and end of the 60° pass.

The time alloted for the desired vehicle rotational velocity changes in executing the Z-LV maneuvers is determined by the maximum allowable rotational acceleration $\ddot{\theta}_L$ (assigned a value of $0.002°/\text{sec}^2$ in Ref. 1.) The CMGs must provide the torque required to execute the maneuvers in the time allotted to prevent vehicle attitude and rate errors. It is evident that 2 CMGs cannot always supply the required torque. When the simulation was rerun with $\ddot{\theta}_L = .001°/\text{sec}^2$, the TACS requirement for the $n_x = 50°$, #2 CMG out case dropped from 137 to 48 lb-sec and for the $n_x = -50°$, #1 CMG out case dropped from 199 to 16 lb-sec. The CMGs were more nearly able to provide the reduced required torque resulting from the increased acceleration time.

Conclusions

The simulation of 3 CMG control of solar inertial orbits, dump maneuvers, and Z-local vertical passes did not disclose control problems.

With 2 CMG control, up to 20 lb-sec of TACS propellant was required for attitude control for some solar inertial orbits and up to 791 lb-sec was required for some 60° Z-local vertical passes. On some dump maneuvers attitude control was ineffective, resulting in attitude errors up to 48°.

Performance was sensitive to the initial momentum state, ranging from good to poor as the momentum was varied within limits reasonable for the initial orbital position.

One source of difficulty with 2 CMGs is that the gimbals occasionally encounter their stops, thus preventing 3 axis attitude control. In some of these cases, removing the "S" function limitation prevented the encounter. Thus it appears that the "S" function limitation inhibits the role of the rotation law in effectively optimizing the gimbal angles.

At low values of CMG momentum magnitude, the steering law produces limited torque **commands**. If large control torques are required at these times, attitude errors develop, sometimes large enough to require TACS assistance for correction. If the torque is required for maneuvering, the problem can be aleviated by increasing the time presently alloted for vehicle velocity changes, thus requiring smaller accelerations and smaller control torques.

Attitude control with 2 CMGs has problems that need resolving.

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1022-WL-mef W. Levidow

References

1. ATMDC Program Definition Document, Part 1, Revision II.

2. Levidow, W., "Effect of Venting and Leakage Torques on Attitude Control of the Skylab Orbital Assembly by CMGs." TM-71-1022-1, March 2, 1971.

3. Elrod, B. D., Anderson, G. M., "Equilibrium Properties of the Skylab CMG Rotation Law", TM-72-1022-2, March 31, 1972.

TABLE 1

Solar Inertial Orbit - 2 CMG Control

η_x	Phase	CMG #1 OUT				CMG #2 OUT				CMG #3 OUT			
		Gimbal Angles		ϕ_e	TACS	Gimbal Angles		ϕ_e	TACS	Gimbal Angles		ϕ_e	TACS
		Hit Stop	Digress			Hit Stop	Digress			Hit Stop	Digress		
0	SI	-	-	0.0	0	-	-	0.4,H	0	x,s	-	1.0,GS	20
	DUMP	-	-	0.2		-	-	0.2		x,s	-	9.0	
	DUMP(c)												
+30°	SI	x,s	x,~~s~~	1.0,GS	20	-	-	0.8,H	0	x,s	x,s	1.0,H	16
	DUMP	-	x,~~s~~	0.4		x,s	-	2.0		-	x,s	0.4	
	DUMP(c)	-	x,~~s~~	0.5						x,~~s~~	-	0.8	
-30°	SI	-	x,s	0.0	0	-	-	0.6,H	0	-	-	0.4,H	0
	DUMP	-	x,s	0.2		-	-	0.2		-	-	0.2	
	DUMP(c)	-	-	0.0									
+70°	SI	x,s	x,~~s~~	0.2,RL	0	-	-	0.5,H	0	-	-	0	0
	DUMP	x,s	-	2.5		-	-	1.0		-	-	0.6	
	DUMP(c)	x,s	x,s	4.0									
-70°	SI	-	-	0.0	0	-	-	0.0	0	-	-	0.0	0
	DUMP	x,~~s~~	x,~~s~~	48.0		-	-	0.4		x,~~s~~	x,~~s~~	40.0	
	DUMP(c)												

Notes: ϕ_e: maximum attitude error, degrees, on any axis during the phase

TACS: Propellant required, lb-sec, during the phase

DUMP(c): Gimbal angles caged 90° before dump midnight

- \- : Satisfactory gimbal performance
- X : Gimbals encounter stops or angles digress from caged values
- s : Performance satisfactory when rerun with "S" function limitation removed
- ~~s~~ : Performance does not improve with "S" function limitation removed
- RL : Attitude error caused mainly by gimbal rate limit
- GS : " " " " " gimbal stop encounter
- H : " " " " " low momentum magnitude

TABLE 2

60° Z-Local Vertical Passes, 2 CMG Control

η_x	CMG #1 OUT			CMG #2 OUT			CMG #3 OUT		
	Gimbal Angles		TACS	Gimbal Angles		TACS	Gimbal Angles		TACS
	Hit Stop	Digress		Hit Stop	Digress		Hit Stop	Digress	
0°	-	-	0	-	-	0	x,s	x,s	583,GS
+50°	x,$\cancel{s}$	-		-	-	137,H	x,$\cancel{s}$	x,$\cancel{s}$	128,GS
-50°	-	-	199,H,RL	-	-	0	x,$\cancel{s}$	-	791,H,RL